Geodynamic processes on sandy slope gullies in central Spain field observations, methods and measurements in a singular system

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Abstract

Gullies developed on sandy lithologies are scarce and few studies have been reported on these landscapes. This paper presents an approach to study such singular landforms. The studied gullies appear on the slopes of a group of mesas and cuestas of Upper Cretaceous sediments located in the Northern piedmont of the Guadarrama Mountains, Spain.

Landforms of these gullied areas were catalogued, characterized and quantified with reconnaissance methods, providing information about the most active geomorphic processes. These are being monitored in a 1.32 ha representative gullied catchment, the Barranca de los Pinos. In its high gradient slopes, where mass movements occur, high resolution topographical surveys are being carried out by Terrestrial Laser Scanning (TLS). On low gradient slopes, runoff and rain splash are being monitored in micro plots; and in the main channel, sediment transport and water discharge are being measured.

This ensemble of methods, some of them novel, is providing patterns of sediment movement within the gully system, and a hypothesis of high activity rates has been confirmed. High gradient sand slopes without carbonate caprock erode fourfold compared to the capped slopes. In the low gradient slopes, those ungullied produce more runoff while exposed sands yield more sediment; sands covered by litter produce the least runoff and sediment. Notably, this catchment yields mainly bedload.

Keywords: soil, size distribution, wind erosion, Tunisia.

1. Introduction

Gullies and badlands are usually associated with clayey lithologies [1, 2]. Consolidated sandstones in desert environments develop specific badland landforms and landscapes, such as pinnacle badland slopes or hodoos [3, 4]. Sand or poorly consolidated sandstone which develop gullies may have a different geologic origin: sedimentary rocks or regoliths of igneous rocks (see Table 1).

Whether gullies on sandy materials are scarce worldwide, or whether it is the scarcity of publications about such landforms is a complex issue. A compilation of geomorphic studies of gullies developed on sands and poorly consolidated sandstones (Table 1) is not large. This contrasts with the literature about gullies and badlands, landforms that have always attracted the interest of geomorphologists [1, 3].

The fact that most of the references on Table 1 derive from the United States and Africa suggests that other continents likely have such gullies which have hitherto received no attention. A rationale explaining the scarcity of gullies developed on sands is their low stability in geo(morpho)logic time spans. Okagbue and Ezechi [5] argue that, due to the physical properties of these materials (high permeability, porosity and void ratio, with low and very low density, if any cohesion),

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Table 1: References on sandy gullies.

	smaterials	references	location	method
	friable sandstones, thin coal beds and thick mudstones (Kirtland & Fruitland Fms.)	Wells and Gutierrez, 1982 [73]	Chaco River basin, New México, USA	regional trends and stratigraphic analysis dating deposits with C_{14} two instrumented catchments (111.2 and 0.025 km^2) with defined HRUs (erosion pins, portable erosion measuring frame, sediment and runoff plots from few to tens m^2 and measuring topography transects in channels)
	poorly consolidated sands and gravels with interdigitated lacustrine clays and silts	Brown, 1983 [74]	Borrego Springs, California, USA	topographical survey of channel geometry painted tracers and scour chains infiltration and void ratio tests
	sandstone and mudstone; upper Karoo Supergroup Katberg Fm.,	Boardman, 2003 [75]	Sneeuberg, Great Karoo, South Africa	aerial photography analysis of historical changes rainfall simulations field observations
	sandy and gravel alluvium	Nichols et al., 2008 [8]	Walnut Gulch experimental watershed Arizona, USA	gauged 7 catchments (0.1-4 ha) with H-flumes and pump samplers of suspended sediment. annual topographic survey in 8 sediment tanks at the outlets of 7 watersheds (35-160 ha).
	sandy hill slope (80 % sand)	Peugeot et al., 1997 [76], Esteves and Lapetite, 2003[6]	Western part of Niger (Sahel)	runoff and sediment plots (closed and open) in different HRU with different sizes, large ones with continuous measurements of water discharges and small ones (1 m^2) with totalize measurements after events nested gauged catchments (4 and 11 ha) with Parshall flumes and electronic water stage recorders rainfall, soil moisture and infiltration rates monitoring
	sandy hill slope	Karambiri et al.2003[7]	Eastern Burkina Faso (Sahel)	gauged nested catchments (0.3 and 1.4 ha) with V-notch weir, water level recorder and, ISCO sampler
	sandstones interbedded with shales and shaly limestone (Ameki Fm); sandstones (Ajaly Fm.)	Okagbue and Ezechi, 1988 [5]	Eastern Nigeria	field sampling for lab determination of density, water content, void ratio and porosity
	dune sand fine- to medium-grained, moderately well-sorted and clay (trace--4 %)	Sweeney and Loope, 2001 [77]	Nebraska Sand Hills of the Great Plains, USA	topographical surveys of alluvial fan and gullies with total station monitor of saturated hydraulic conductivity Trenching in alluvial fans and sampling
	sand dunes	Védie et al., 2008 [78]	Mars	laboratory simulations
regolith	sands, gravels and clays with kaolinite and illite of deeply weathered granite regolith	Lam, 1977 [79]	Tai Lam Chung region, Hong Kong	portable erosion measuring frame
regolith	loamy sand soils on the Bathurst Granite	Crouch, 1990 [40]	Central Tablelands of New South Wales, Australia	erosion pins

once gullying is initiated, erosion processes propagate rapidly. Therefore, their 'natural' geomorphic evolution is destined to the disappearance of the sandy gully landforms, so that their origin may be related to recent geomorphic time.

Regardless of the reason, the fact is that these landforms have not been profusely studied: hitherto studies of sand gullies (excluding [6], [7] and [8]) have been merely based on reconnaissance methods for geomorphic analysis (Table 1). Hence, obtaining accurate data on the geomorphic activity of these sandy gullies by means of technologically advanced methods is expected to cover a knowledge gap, as introduced in this paper.

Additional reasons that justify the importance and interest of understanding the dynamics of the gullies analyzed here are their interaction with human activities, the complexity of interpreting their origin and development, and the use of this information for the management and reclamation of disturbed lands with similar characteristics. Even though the effects of the erosion in the studied gullies does not present high danger, they frequently affect the regional economic, social and ecological dynamics because they bury roads and buildings [9], crop fields and produce soil loss in forest areas.

Because the base level of these gullies is formed by rivers flowing on high resistance metamorphic rocks (Fig. 1.c), the incision rate of which is very low, the origin and development of these gullies should be linked with environmental changes, human activity or climatic changes [1] [2] [10]. Actually, the triggering factor of these gullying processes has been suggested to be quarrying activities dating back 800 yr [11, 12].

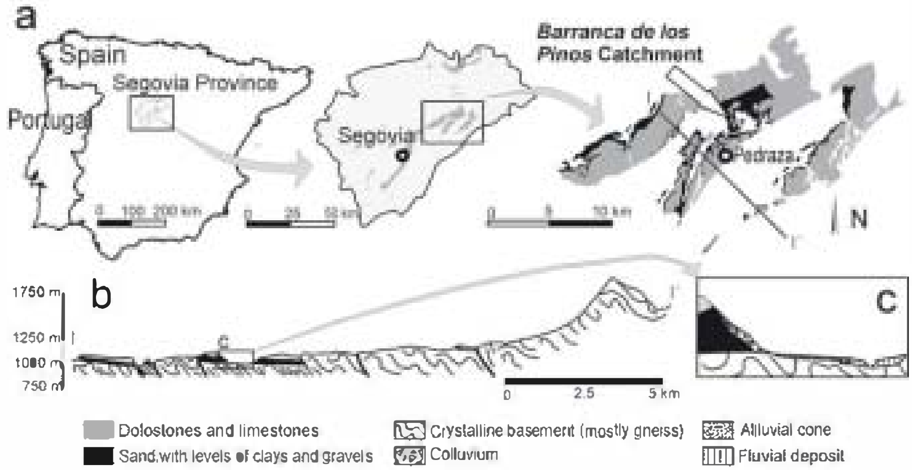

Fig. 1: a) Location of the study area. The mesas and cuestas are capped by limestone and dolostone rocks (grey colour). The hillslopes, dissected by gullies, are underlain by horizontally bedded silica sand deposits, with thin intercalations of clay and gravel (black colour). b) Draft of the geological profile of the area, where the mesas and cuestas developed on sedimentary rocks can be seen. c) Zoom into the slope of one of the cuestas and its nearby alluvial plain, showing the Quaternary deposits, such as the carbonate colluvium covering the ungullied slopes, the alluvial cone at the slope toe and fluvial deposits

Finally, quarries in the same geologic unit for extracting sands or clay minerals are common in the eastern part of the Iberian Peninsula, and similar landforms occur in their abandoned quarries and spoil heaps [13]. In some of these areas, sediment transported into rivers from mined areas has been documented as a severe environmental problem [14]. Therefore, a study of the geomorphic activity in sandy slope gullies is expected to shed light on the dynamics of sediment sources from mining areas with similar characteristics and it may be useful for improving reclamation projects in these landscapes.

Considering all the described circumstances, the specific objectives of this study are (a) identifying and describing the landforms that denote active processes in this set of gullies; (b) recognizing their most active processes and (c) studying, with high spatial and temporal resolution, those processes described as the most active in a representative catchment. Objective c is aimed to initiate provision of temporal and spatial information on the dynamics of this geomorphic system. This allows achieving a broader objective, which is: to identify and understand the relevant geomorphic processes of this environment, by evaluating the rates of the different processes acting within these landforms, their frequency of occurrence, their triggering thresholds and the interconnection and coupling between them [15, 16].

The hypotheses we initially raised were twofold: (1) there is a high diversity of landforms within these gullies due to their geomorphic setting, each landform feasibly mapped; and (2) the rates of geomorphic activity and connectivity within these gullies are high. After testing hypotheses (1) and (2), other hypotheses were formulated: (3) among the high gradient slopes, uncapped gully headwalls and erode faster than their capped counterparts; (4) the hydrologic and erosive response of the low gradient slopes is conditioned by the presence of surface deposits or litter, splash erosion being significant in exposed sandy slopes, and (5) most of the sediment yield in the channels is bedload.

2. Study area of the Sandy Gullies

The study area is located in the Northern piedmont of the Guadarrama Mountains, within the Segovia Province of Central Spain (Fig. 1a). Sand slope gullies in this region (the Pedraza district) occupy an area exceeding 18 km^2 and deeply dissect a set of mesas — residual platforms — and cuestas — asymmetrical ridges with distinctive scarp and dip slopes (Fig. 1b and 2a). At this location, Upper Cretaceous marine (limestone and dolostone) and fluvial (clayey and gravelly silica sand) sediments outcrop. Whereas the limestones and dolostones appear in the caprock of the mesas and cuestas, the sands underlie the caprock, forming the hillslopes and outcropping within the gullies (Figs. 2a and 2b). Where slopes are ungullied, they are covered by a carbonate colluvium comprised of reworked caprock sediments (Fig. 1c).

Rendzic leptosols [17] have developed on the consolidated limestones and dolostones of the mesas and cuestas platforms and dip slopes. Colluvial regosols typify the carbonate colluvium covering the sand formations. Most of the gullied surfaces are exposed, lacking a soil cover. Reflecting local geomorphic stability, sandy cambisols have developed nearby.

The climate is temperate with a dry and mild summer: Csb, according to Köppen [18]. Based on the Matabuena and Segovia weather stations of the National Meteorological Agency of Spain [19], the climate is characterized by a moderate average annual precipitation (680 mm) and temperature (11.4°C). Due to distance from the sea, high altitude (1050 m a.s.l.) and proximity to the Guadarrama Mountains, winters are long and cold. Temperatures below -10°C are not uncommon and the number of snow days averages 13 annually. The summers are short and dry.

Extensive livestock farming of this area for more than a millennium transformed formerly dense woodlands to open woodlands covering the mesas and cuestas. However, a gen-

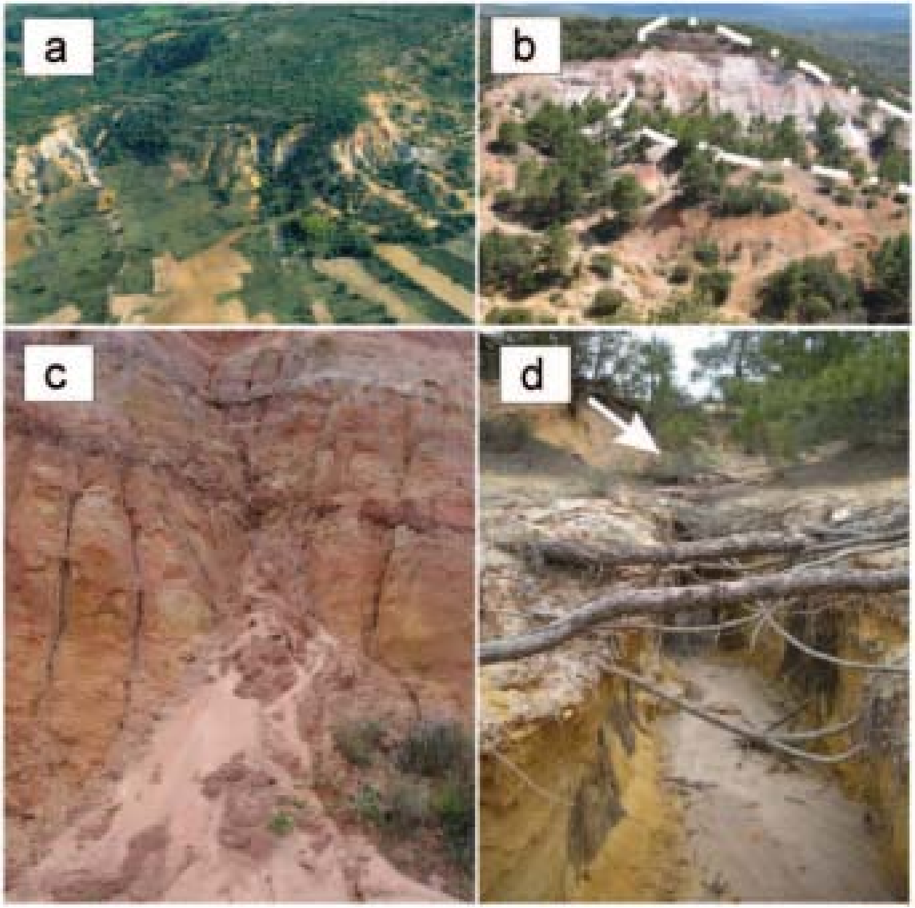

Fig. 2:
a) Oblique aerial view of gullies (Pedraza region) developed on sandy sediments on the slopes of a small mesa; note the high vegetation cover in the surroundings
b) View of the *Barranca de los Pinos* gullied catchment (divide in white line), located in one end of a narrow mesa covered with dense vegetation of holm oak and savin juniper. The steeper foreground is outside the catchment. The less steep (mid-photo) corresponds with the interior of the *Barranca*, colonized with pine stands of *Pinus pinaster*. The main channel drains this area to the right of the image. The lined slopes of the background are in part (central area) capped by limestones and dolostone. Most of the gullied area is underlain by sands. The rest of the gullied surface is covered by limestone-dolostone colluvium. c) Erosive activity of some of the steep sandy slopes (scars of small falls are seen and also perennial inner rills), their variegated beauty and the resultant, non-cohesive availability of eroded material. d) The gullied main channel draining the *Barranca de los Pinos*. Headcut retreat is limited by these roots and by organic debris (background) and monitored from a fixed stake (pointed with an arrow)

eralized abandonment of these rural areas since the second half of the 20^{th} century allowed the density vegetation cover to increase [11, 12], being presently a rather close forest excepting within the gullies (Figs. 2a and 2b). These woodlands comprise holm oak *(Quercus ilex,* subsp. *rotundifolia),* white savin juniper *(Juniperus thurifera)* and juniper shrubs *(Juniperus communis* subsp. *hemisphaerica)*. Vegetation cover is scarce within the gullies due to the high instability of the substrata — by highly active processes of erosion and sedimentation — and different pH conditions — slightly acidic or neutral within the gullies, slightly basic outside [20]. Nonetheless, some pine stands of *Pinus pinaster* colonize the sandy substrata within the gullied areas.

Based on historic evidence, it has been suggested that the formation of these gullies was triggered by quarrying activities dating from at least 800 years ago [11]. Additional indicators supporting this hypothesis include: (a) the climate conditions allow current dense formations of native vegetation growing where the slopes are not incised; (b) most of the gully heads are located downslope of unequivocal evidence of ancient limestone quarrying near village sites [12] and they are unrelated to slope hollows — in fact most of them appear on hillslope 'noses'; (c) the local base level in the region has remained very stable during the last millennia — the mesas and cuestas rest on a hard gneiss rock basement, into which the fluvial network has been formed.

2.1. The Barranca de los Pinos experimental catchment

To study the dynamics of this geomorphic system, the *Barranca de los Pinos* catchment was selected because it was assessed to be representative of the set of gullies in the studied area (Fig. 2b) in terms of size, slope gradient, landforms and lithology. The 1.32 ha catchment has high gradient slopes (>30°) in 29.0 % of the catchment. Hillslopes dominantly face South and North, are dissected by secondary gully channels, somewhat more abundantly in the North facing slopes. The drainage density of the channels visible in a 0.5-m pixel orthophoto is 0.041 m^{-1}. The main channel heads westwards with a high longitudinal slope (0.066) and its bed grain size (see location of measurement in Fig. 3) is medium to coarse sand (D_{50} = 0.555 mm) with 93.2 % of sand sized material, 2.6% of silt and clays and 3.9 % of gravel. In the main channel there is an entrenched gullied reach (Fig. 2d) with friable, vertical sandy walls and exposed horizontal shallow roots (Fig. 2d).

Only 9.6 % of the catchment is ungullied, including limestone and dolostone caprock and slopes covered by a thick limestone-dolostone colluvium. The gullied area outcrops sands of two geologic formations: *Arenas y Arcillas de Segovia* (hereafter termed Segovia sands) in the upper part, and *Arenas de Carabias* (Carabias sands) in the lower catchment [21]. The main reported textural difference between the sands is that the Carabias is finer grained than the former (the median of the fraction finer than 2 mm is 0.255 and 0.400 mm in the Carabias and Segovia sands

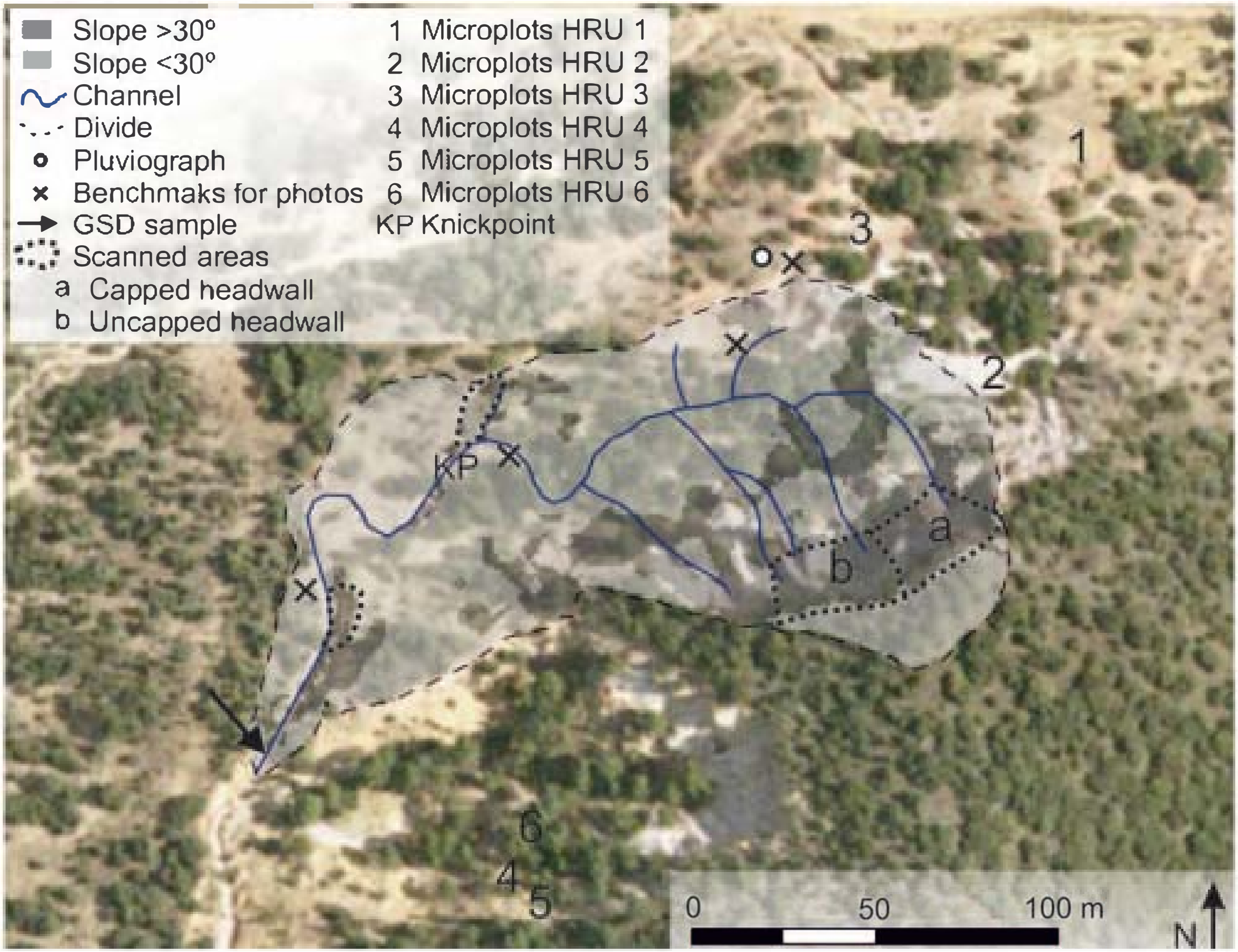

Fig. 3: Landform map. Units described (1) high gradient slopes, (2) low gradient slopes, (3) channels. Location of pluviograph, sampling points, scanned areas, benchmarks for the repeat photographs of the high gradient slopes, microplots and knickpoint

respectively). The gullied sandy surface is in part (12.3 %) covered by a thin colluvium mobilized from the ungullied slope; 18.5 % of it is covered by pine vegetation, the rest bare or covered by scattered shrubs.

The catchment was divided according to geomorphic activity based on a reconnaissance study [10], into: (1) high gradient slopes (> 30°) susceptible to mass movements and/or severe runoff erosion; (2) low gradient slopes (< 30°) where rainsplash and overland flow occur; and (3) channels dominated by ephemeral fluvial processes (Fig. 3).

High gradient slopes within the catchment occur as i) gully headwalls with caprock, ii) without caprock, iii) sandy channel banks covered and iv) uncovered by colluvium. Caprock forming the headwall comprises 9.5 % of the gully perimeter and is intensely fractured, making this area prone to rock falls. The sandy headwall without caprock is covered by variably thick carbonate colluvium producing shorter, lower gradient sandy slopes, or exposed sands forming vertical headwalls. Some sand banks are steep, likely due to increased strength derived from tree roots. Other steep, uncovered sand banks produce sand flows and occasional dry mass movements.

The climatic conditions for the period of the implemented methods, field observations and measurements reported here (May 2007-December 2011) were dryer than average: total rain recorded during the hydrological years 2007/08, 2008/9 and 2009/10 were respectively 84 %, 55 % and 85 % relative to the long-term average. For these respective hydrologic years temperature was slightly (8, 2 and 2 percent) warmer. However, the spring and summer of 2008 and the winter of 2009-2010 were rainier than the average. An extreme event was recorded on September 2008, with 69.4 mm maximum daily precipitation and a 72.4 mm h^{-1} maximum 30 min intensity.

3. Methods

3.1. Identifying and describing the landforms and respective processes in the gullies

Active geomorphic processes are not normally observable, however their results are; therefore from the perspective of a qualitative study of landforms (signs of erosion and sedimenta-

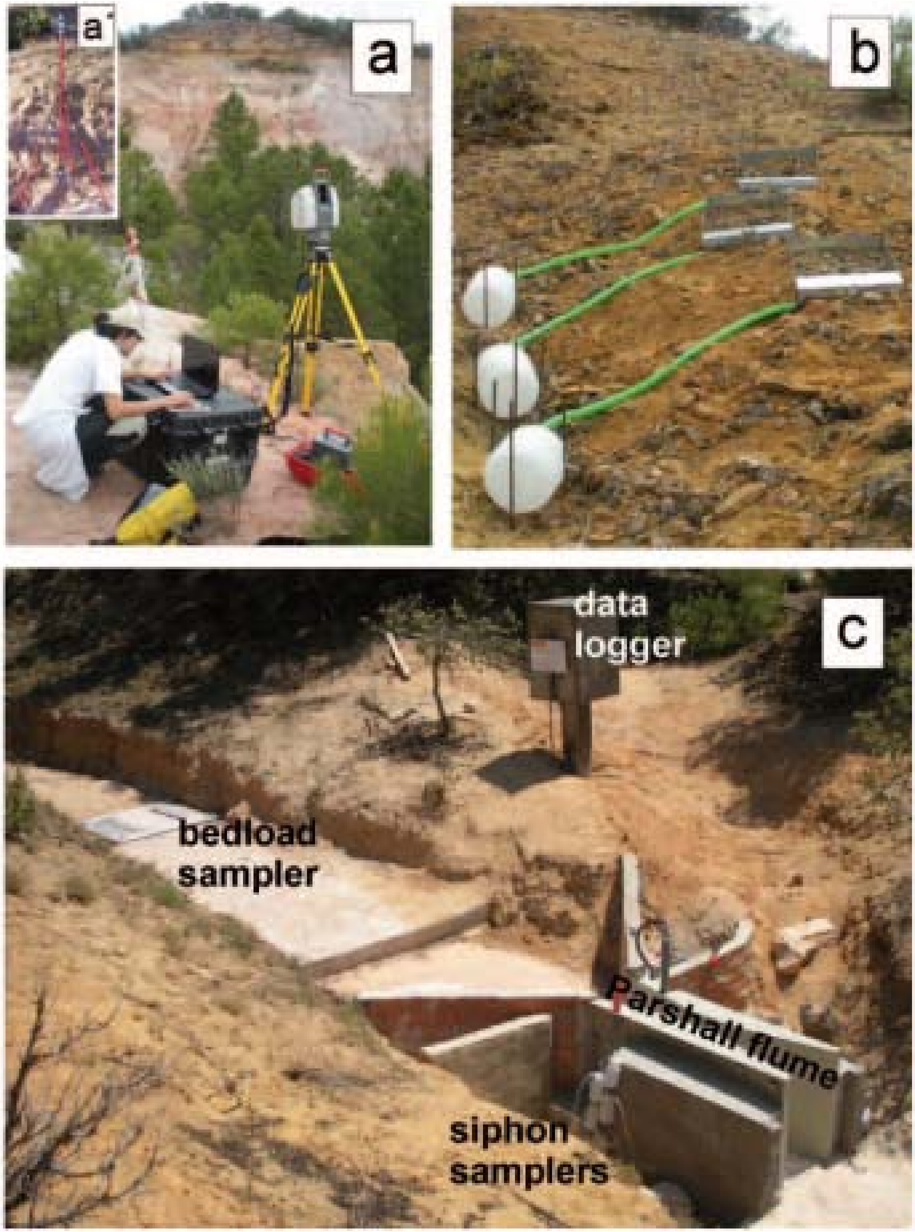

Fig. 4: Methods (a) Terrestrial Laser Scanner (TLS), in the background is the capped headwall of the *Barranca de los Pinos* gully; (a') detail of the twin target; (b) HRU monitored with three replicas of micro plots, (c) equipment installed at the outlet of the catchment to monitor water, bedload, suspended sedimentand solutes

tion) it is possible to infer which are the active processes. With this propose in mind, a field survey was undertaken in 75 local gullies, identifying landforms with reference to active processes and locating their position within each gully. In order to systematize this survey, a form was filled for each gully. Meanwhile, suitable locations for monitoring processes were established.

3.2. Identifying and recognizing the most active processes

Reconnaissance methods were applied in several catchments to initiate estimation of rates of activity of the most active processes dominating each landform. These methods are based on calculating the loss or accumulation of sediment; this method is adequate when the rates of erosion and sedimentation are easily identified and when previous data are unavailable [22], as applicable to these gullies.

Creep was monitored at a recent and an ancient location of debris deposits by painted stones or collars [22] aligned in a straight line and marked with two fixed 50 cm rods. Soil creep was also monitored in an area with existing pine trunks by driving equidistant and aligned short pins or nails [23]. For both methods the displacement of painted stones or nails was seasonally measured. The steepest slopes (rock cliffs, near vertical sand slopes and clayey zones prone to mudflows) of the 75 surveyed gullied catchments were annually photographed to identify the occurrence of gravitational processes.

Splash and sheet erosion were monitored with 60 erosion pins [24] and 12 pedestals in an inner sandy gully divide and in its close inter-rill zones. Sheet erosion rates were also measured with dendrogeomorphic techniques (Bodoque et al., 2011 [25]). The differences between the locations, the two methods and the slope aspects were assessed by applying the Mann-Whitney non parametric test.

Sediment yield was measured at the outlet of two different gullied catchments after each runoff-producing rainfall event with two types of bedload totalizing samplers; both of them were installed before the beginning of the hydrological year 2007-2008. In one of the basins, a gabion was installed 32 m downstream of a knickpoint, where the channel had vertical walls. The gabion retained bedload and was permeable to water and suspended sediment. Vertical iron rods were equidistantly installed within this small check-dam. The channel and catchment boundary were surveyed with a total station. To calculate the density-based specific sediment yield, the topography of the deposit was recorded by measuring the exposed height of the bars. In another 0.1 ha catchment, a similar 2.5 m^3 totalizing pit sampler [26] [22] was installed. The trapped sediment was cleaned and weighted and sediment samples were analyzed for moisture content to calculate its dry weight. During several intense storms, the amount of sediment deposited in alluvial cones that buried the local roads was volumetrically estimated.

3.3. *Spatio-temporal variability of the most active geomorphic processes*

Once the landforms were described and the initial results were obtained from the reconnaissance methods, the *Barranca de los Pinos* catchment was chosen to be representative - in terms of size, slopes, landforms and lithology. This catchment was selected to implement in it a series of methods allowing accurate spatiotemporal measurements of the most active geomorphic processes (Figs. 2b and 3).

A detailed topographical survey was undertaken with a differential GPS (Leica GPS1200) to describe the morphometry of the catchment. Altogether 938 field points recorded in the catchment were distributed along breaks of slope: divides, thalwegs and lines defining scarps faces. A 2x2 m Digital Elevation Model (DEM) was derived from the topographical survey.

The grain size distribution (GSD) of the channel was determined by one sample of the bed located at the catchment outlet (see Fig. 3), because no longitudinal variability of GSD was observed in the channel, according to field visual observations. The one-to-two centimetre depth of the channel bed deposit was sampled in a 2-m long by 1-m wide reach weighing 11.5 kg. The coarsest bed material had b-axis of 3.4 cm, representing 0.29 % of the bed material of the size class of 0.75 % [22]. The sample was sieved at 1Φ intervals and lower-truncated at 0.062 mm.

Rainfall in the *Barranca de los Pinos* catchment is being monitored by a tipping bucket recording rain gauge (0.2 mm accuracy) installed at a height halfway between the outlet and the highest elevation in the catchment (see its location in Fig. 3). Temperature data of the studied period were obtained from the Segovia meteorological station of the Meteorological National Agency (AEMET) [23].

Techniques utilized to monitor surface processes in the catchment vary according to the gullied zones (see Fig. 3).

High gradient slopes are being monitored by repeat photography and Terrestrial Laser Scanning (TLS). Both are applied at four sites in the catchment (Fig. 3) representing the four typologies of high gradient slopes. Their selection was based, among others, on good visibility.

Repeat photographs are taken from fixed points after each sediment-transporting rainfall event. Both benchmarks and selected zones are marked in Fig. 3. The method is easy, cheap and provides qualitative information about the location where sediment moves. It adds details concerning landform changes between scans, hence timing of hillslope changes. Detailed topographical surveys using a Terrestrial Laser Scanner (TLS) were undertaken to quantify topographic changes (Fig. 4a). Being non-intrusive and of high precision, TLS allows obtaining high resolution topographic information. Among others, TLS allows monitoring vertical walls which otherwise cannot be accurately surveyed. The TLS used here (Leica Scan Station 2) measures up to 50,000 pts sec^{-1} with a 2-mm precision at a scanning distance <120 m. The selected locations were identified and scanned with a spatial resolution ranging from 0.5x0.5 cm to 10x10 cm. Such span depends on the size and morphology of the landforms to be scanned.

To cover the entire surface, at least two different conventional TLS survey scan positions were used to avoid dead centers [24]. Repeat scanning involved fixed accurate FENO benchmarks, with survey caps, which offer a high accuracy and are stable in time, as they are strongly anchored to the soil; during the scanning, these benchmarks were signalled using a vertically-held twin target (Fig. 4a') supported with a tripod instead of by hand, thereby increasing accuracy. Data accuracy, or systematic error equal to the difference between the measurements and the true value, is calculated as the Root Mean Square (RMS) of the distances in the vertical (z) axis between the targets measured using both the TLS and the Total Station (Pentax R-315N); assuming that Total Station measurements are the true value [25], even though its accuracy is of 3.1 mm at the maximum measured distance.

Point cloud locations which did not correspond to the topographical surface were identified and manually deleted in the Cyclone® software. Cloud data points were exported to the 3DReshaper® software, with which a Triangulated Irregular Network [24] digital model was constructed. The accuracy of the model was determined by comparison of differences in z-axis between points measured with a Total Station and the same position in the model [25]. Repeat scanning allowed identification of topographical changes as well as determination of volumetric changes [26]. This innovative technology allowed measurement of complex and steep slopes.

Lower gradient slopes were monitored as Hydrologic Response Units (HRUs) also termed Erosion Response Units, ERUs e.g. [27]. An HRU is defined as an area of homogeneous hydrologic characteristics such that the response to climatic forcing is uniform [28]. Thus, for a given rainfall event, HRUs vary in response to soil water dynamics by influencing infiltration and runoff rates [29]. As a result, HRUs differ in magnitude of erosion and type of sediment transport processes [30]. Delineation of HRUs depends on scale, available information and methods. Within the *Barranca de los Pinos* catchment, the delineation was made by use of an aerial orthophoto and a 2x2 m DEM obtained with a GPS topographical survey and checked with field observations. The parameters taken into account to delineate the HRUs were the following: spatial distribution of land use (if the slope is gullied or ungullied), cover (by surperficial deposits or litter), soil hydrologic condition (given by lithology and texture) and topography in the 0°-30° range of slope. Table 2 provides these HRU characteristics along with surface mechanical resistance.

To assess differences in runoff and erosive response, slightly modified Gerlach boxes were installed on 0.25 m^2 micro plots [31], see Fig. 4b. A total of 18 plots, 3 plots for each of the 6 HRUs, with similar aspect and gradient, were enclosed by metal sheets. It is recognized that edge effects are large and life spans are shorter for small closed plots, but these effects are expected to be similar for all plots [32]. Each of the HRUs was sampled for soil textural analysis, each sample composed of three sub-samples. The analysis was

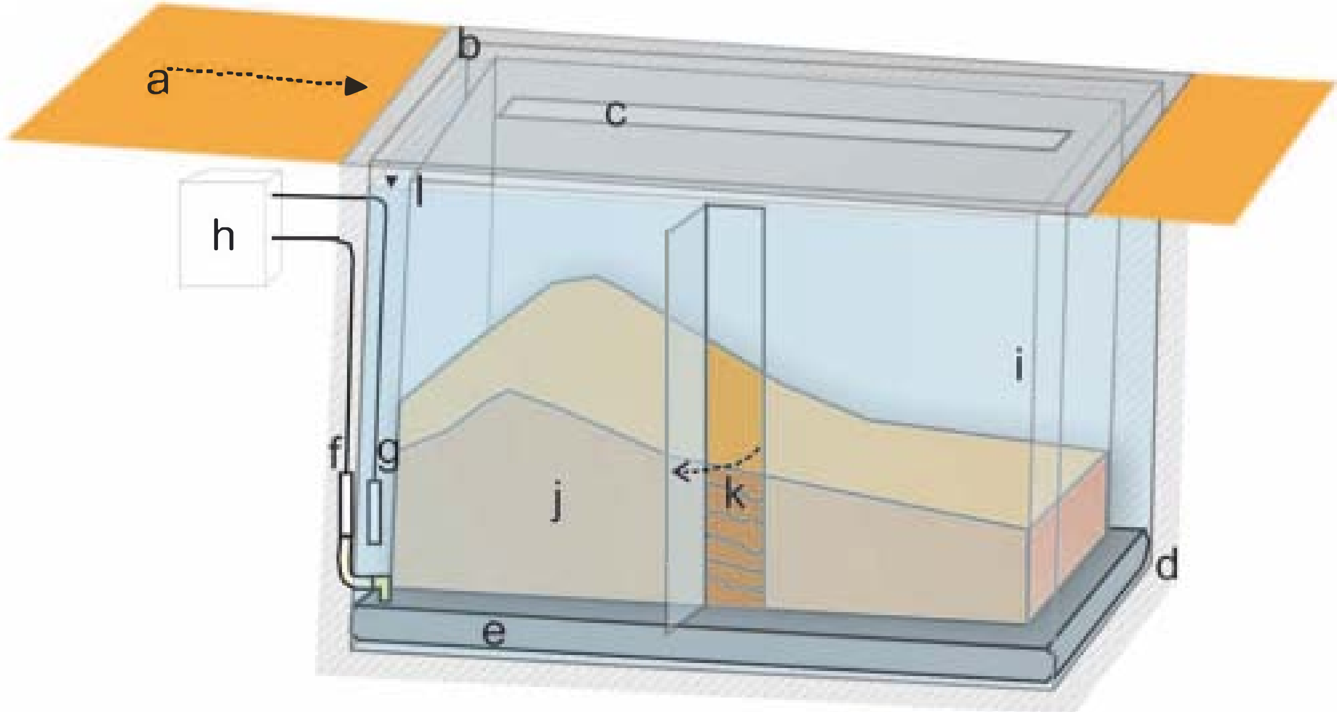

Fig. 5. Bedload sampler scheme where it can be observed: a) channel bed and flow direction , b) metal lid covering the sampler; c) slot in the lid where the bedload enters into the sampler; d) concrete box, e) pneumatic pillow connected to a f) pressure transducer; g) pressure transducer that measures the water depth, both pressure transducers are connected to a h) datalogger; i) metal box held by the pneumatic pillow where the j) sediment is accumulated, k) lateral window in the metal box, which allows a sedimentological analysis of the bedload; l) the channel is ephemeral, so that the sampler is maintained filled with water up to the maximum, because it starts to monitor bedload when it is completely full with water

made by sieving the fraction smaller than 2 mm, including Robinson's Pipette method to quantify the proportion of silt and clay. Surface mechanical resistance was measured (under wet conditions) with a Geotester Pocket Penetrometrer perpendicularly to the slope using a large (25 mm) tip. Altogether 7 to 21 locations were tested depending on spatial variability (mean values are shown in Table 2). Runoff and sediment collected from the microplots were sampled after each rain event, considering a single event as a rain episode which is separated from the following by more than 24 hours. Runoff volumes were measured in the field (± 10 ml accuracy test tube). An aliquot of the runoff was sampled for determination of sediment concentration. Coarser sediment collected in the Gerlach devices was separately sampled, dried and weighed to determine the sediment yield of each microplot.

In the channel, the upstream migration of the main knickpoint was monitored by repeat measurement of the distance to the knickpoint from a fixed stake (arrow in Fig. 2d); knickpoint height was also reiteratively.

Fluvial activity monitored at the catchment outlet includes water discharge, bedload, suspended and dissolved loads. Bedload discharge is automatically and continuously monitored by two independent, cross-sectional aligned Reid-type (formerly termed Birkbeck) slot samplers (Figs. 4c and 5) [33]. Maximum slot width, 160 mm at both samplers, represents 26 % of the channel width. The cumulative mass of sediment entering a sampler is monitored by a vented pressure transducer connected to a pre-calibrated pressure pillow, upon which an internal metal box is located; however the pressure of this sensor is also affected by the pressure produced by the water column. Therefore, a separate, calibrated and vented pressure transducer located, between the outer and inner boxes, monitors only the hydrostatic pressure of the water column. This pressure is subtracted from the pressure registered in the pillow, so that the net change in a time interval reflects the bedload entering in the sampler [34]. Data from the pressure transducers is measured every 10 seconds and the average is registered in the data logger each 30 seconds. The volume of each inner box is 0.225 m^3, a design based on prior specific sediment yield assessments in the catchment monitored with the totalizing pit sampler [35]. The effectiveness of the sampler is considerably reduced when it is 80 % full [36], and its sensitivity was estimated to be 0.3 kg [34], being in fact 0.25 kg after it was tested by calibration. The length of the slot is 65 cm, so designed given that 90 % of the bed material grain size distribution is sand, in part transported by saltation. The saltation length of sand was estimated using

$$\lambda_b/D = 3D^{*\,0.6}\,T^{0.9} \quad (1)$$

where λ_b is the saltation length with an accuracy of 50 %, D is the particle diameter, D^* the dimensionless diameter, and T the transport stage parameter [37]. Applying this equation and using the D_{50}, 0.04 as the Manning parameter [38] and a maximum water depth of 30 cm, the saltation length was estimated to be 36 cm (±50%); therefore, the maximum length would be 54 cm. However, as the design of the boxes allowed it, the slot length was finally built having 65 cm, to have a security factor. The metal box of the sampler has a lateral window allowing observation of the sediment deposit and facies-based sampling once the box is lifted onto the channel bank (Fig. 5).

A Parshall flume was installed downstream of the bedload sampler to monitor water discharge. The elevation of the water surface is measured at a stilling well by a pressure transducer. This transducer is also connected to the data logger, so the measurements of bedload and water discharge are simultaneously logged. In some events, a 2-3 cm thick sandy sheet was deposited at the bottom of the flume. During the end of the recession of these events, the Parshall-based hydrographs appear to have a long recession tail. However, water depth registered at the location of the bedload sampler enabled to determine the duration and magnitude of these flow events. These very low recession data were excluded.

Table 2: Characteristics of HRUs

ID HRU	lithology	Cover	texture S %	texture CM %	texture CL %	surface mechanical resistance kg cm^{-2}
1*	carbonate colluvium	thick colluvial	68.9	11.9	19.3	1.1
2	sand (Segovia Fm.)	None	100	0.0	0.0	0.9
3	sand (Segovia Fm.)	thin colluvial	88.5	1.5	10.0	0.4
4	sand (Carabias Fm.)	None	98.3	0.5	1.3	0.9
5	sand (Carabias Fm.)	thin colluvial	95.2	0.0	4.8	0.4
6	sand (Carabias Fm.)	dead pine leaves	98.2	1.0	0.8	1.3

*ungullied slope, the rest of the HRUs are gullied slopes.

Altogether six siphon samplers installed on one side of the narrower stretch of the Parshall flume were placed at increasing heights to sample suspended sediment and the aqueous solution during hydrograph rise. As the section is narrower than the width of the nearby *Barranca de los Pinos* channel, water depth is higher than in the channel, thereby, facilitating sampling of suspended sediment. Given the shallow water depth of most of the events, only five events filled the second bottle exceeding depth of 7.7 cm. Figure 4c shows the setting of the equipment at the outlet of the experimental catchment.

4. Results: Rates of Geomorphic Processes

4.1. Identifying and describing the landforms and respective processes in the gullies

A catalogue of landforms for each of the 75 gullies was elaborated. Figure 6 is a synthesis of this catalogue, showing a photograph of each of the landforms which characterize most of the surveyed gullies. They have been organized according to location within the gully and the processes that formed them.

Fall scarps are located in the carbonate caprock of the mesas and cuestas, at the highest reaches of the gully headwalls; they are conditioned by rock joints. Here rockfalls (falls, topples and collapses) occur, and their deposits form debris cones, screes and small debris streams, depending on the pre-existent shape of the slope.

Sands with higher cohesion (sandstone) form vertical or nearly vertical scarps, some also following vertical joints, which condition fall occurrence. At the scarp toes, sandy talus slopes of less consolidated sand appear.

Head scarps of small slides and slumps are observed in the headwalls of the gullies where there is no caprock. Their deposits have not been recognized, which suggests that the mobilized sediment is highly erodible.

Weathering processes give rise to popcorn structures and desiccation cracks at clayey levels, and small deposits of clay slabs accumulate downslope.

Hemispheric and half-funnel hollows appear on upper clayey strata of gully headwalls, the deposits of which are well defined mud lobes, sometimes with recognizable levees. They are interpreted as small mudflows, conditioned by high slope, clay material and water content. Very small sand lobes with levees are formed at the bottom of sandy talus slopes. The levees appear to have had high viscosity; hence they are interpreted to result from sand flows with some content in clays and high water content. Curved pine trunks are an indicator of slow creep movement. At the headwalls of the uncapped gullies, the colluvium from the ungullied mesa and cuesta slopes is being slowly mobilized by creep. Pedestals and exposed roots in the exposed sands of the inner divides indicate that rain splash erosion and sheet flows are active in these areas. Shallow small rill channels cut the slopes following parallel patterns. They are permanent in the exposed sands and semi-ephemeral in the sandy talus slopes, hence their permanence appears to depend on rate of cementation. Permanent channels with dendritic patterns created by gully erosion form the main drainage of these gullies. The divides between the inner gullies are in parts rounded and in others knife-edged (where the sands are more cemented). Residual landforms of these divides are hoodoos, sometimes capped by a boulder. Talus flatirons, remains of the original ungullied slopes covered by thick colluvium, appear commonly between two adjacent gullies.

The gully collectors have variable lengths, low sinuosity and high slope. They have a sandy bed with very few scattered gravel-sized stones. They have almost flat beds, although very shallow bedforms are observed after ephemeral floods. Their banks are vertical to sub-vertical. In these banks, small slide scarps are observed. The deposits of these processes have not been recognized, which suggests that the processes occur while the water flows. These undermine the channel

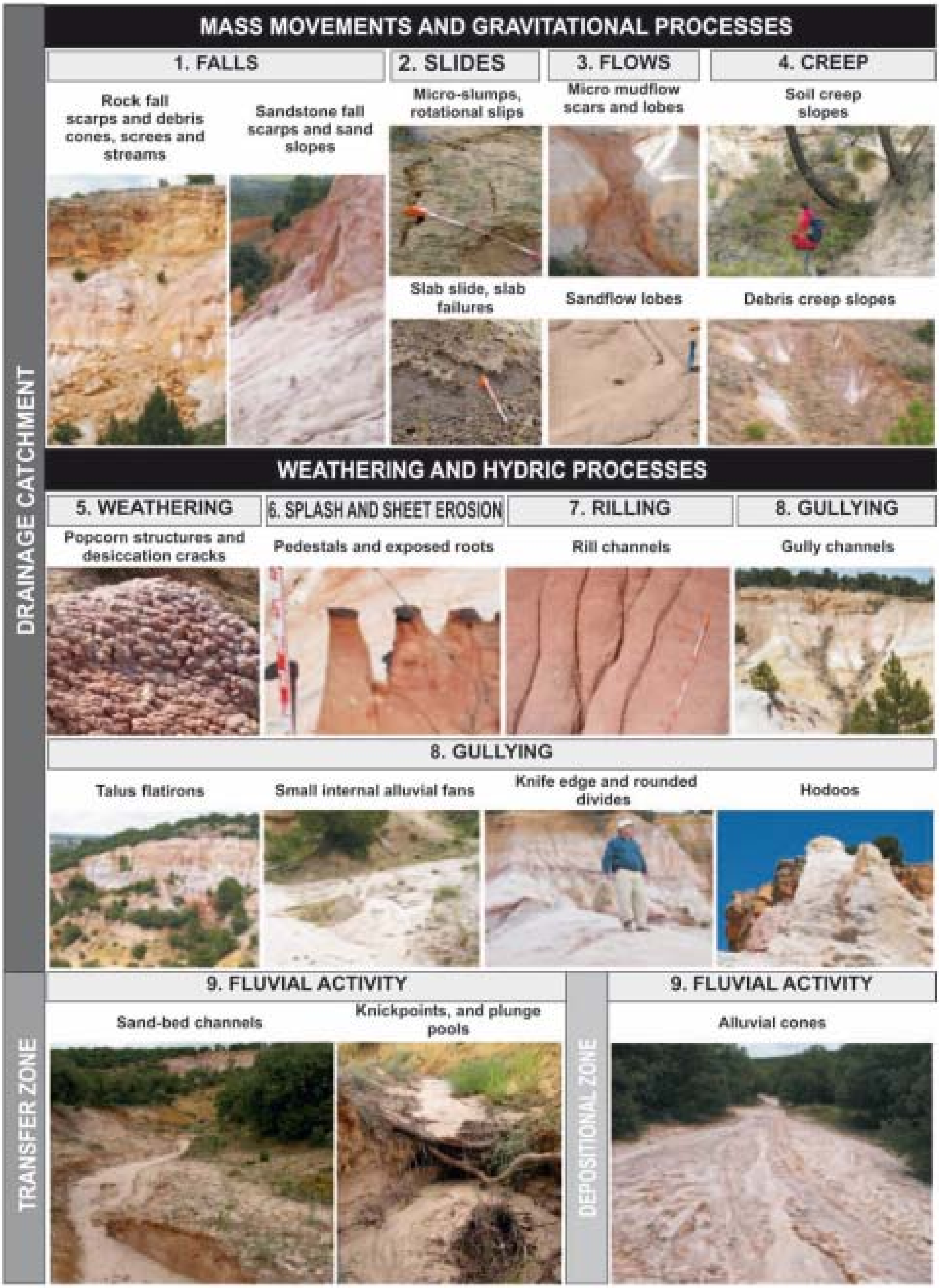

Fig. 6: Landforms that denote act.ve geomorphic processes within the studied sandy gullies

banks, triggering slides and erode their deposits. Small fall scarps and fall deposits have been observed to occur mostly in winter, which may indicate that temperature changes can produce these falls. Deposits are always eroded after flow events occur. Knickpoints are usually controlled by obstacles in the channel, such as cemented strata, stones or transverse roots. Turbulent water flow at the knickpoint base forms scour pools and causes the collapse of the obstacles (outside roots, which are left bare, see Fig. 2d). The upstream migration of the knickpoints maintains the verticality of these small waterfalls.

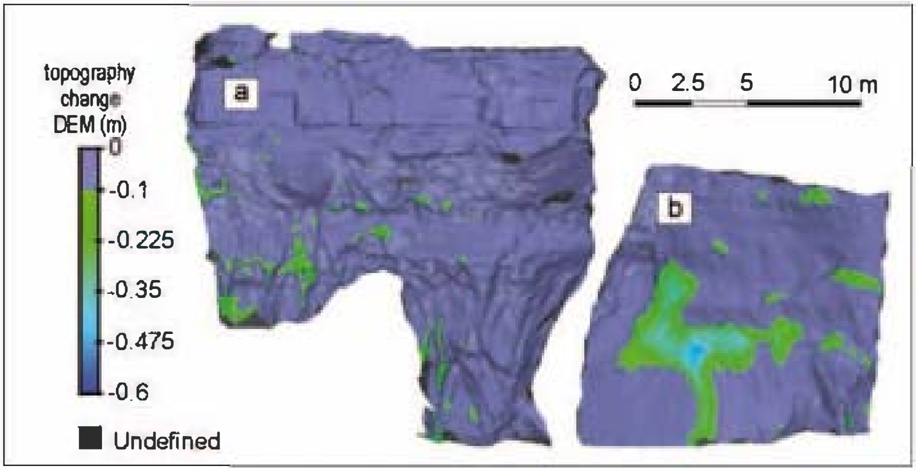

Fig. 7: Results obtained with the TLS in two headwall zones, (a) with caprock, calculated erosion rate of 6.6 mm yr^{-1} and (b) without caprock, calculated erosion rate owf 28 mm yr^{-1}. The erosion is represented light grey

A conical, low gradient depositional zone occurs at gullied sedimentation sites. After the end of ephemeral flow events very shallow bars are observed. Buried herbaceous vegetation, bushes and tree trunks also characterize these cones.

The abundance of landforms with very recent activity of erosional and depositional processes in the gullies is evidence of considerable geomorphic activity.

4.2 Identifying and recognizing the most active processes

No sign of soil or debris creep was detected from the measured displacement of aligned painted stones and nails. Based on annual repeat photography of the steepest slopes of the surveyed gullied catchments, frequent mass movements were identified to occur on this high-gradient terrain. These are mudflows, rock falls and sandstone falls, which mobilized considerable volumes of sediment being the observed movements volumetrically above 1 m^3.

The erosion pins monitored during three hydrological years registering 11.9 mm yr^{-1} average erosion and 16.4 mm yr^{-1} maximum erosion during the first year. The survey of the height variation in the pedestals could only be undertaken one year, because they were later eroded. These showed an average erosion of 10.6 mm yr^{-1}, with a maximum erosion height for a single pedestal of 18 mm yr^{-1}.

Until completely full in June 2008, the gabion trap registered ten sedimentation events, recording a specific sediment yield of 45.0 t ha^{-1} yr^{-1} (for a 10-month period) The pit sampler was operative during three hydrological years, registering 33 sedimentation events, with an average specific sediment yield of 58 t ha^{-1} yr^{-1}, of which 66 % was produced during a single September 9, 2008 event with 69 mm total precipitation in 173 min and a 72.4 mm h^{-1} maximum intensity in 30 minutes. According to the Intensity Duration Frequency (IDF) curves, it corresponds at this site to a return period of 175 years using MAXIN [39]. For the 33 sedimentation events, no good correlation between specific sediment yield and rainfall was observed, although correlation is better with the maximum 30 minute rainfall intensity (I_{30}). For the latter, a regression coefficient of 0.47 for a linear relationship (SY = 0.37 I_{30} - 1.21) was obtained with respect to events with I_{30} < 25 mm h^{-1} and 0.97 when the extreme event is included.

The sediment volume which was deposited in cones in the vicinity of the town of Pedraza was measured once, on May 25th, 2007 (see Fig. 1 for its location). A volume of 31.5 m^3 and a density of 1.4 g cm^{-3} yielded 44.1 tons for a catchment of 15 ha (calculated with the 5 m DEM), or a specific sediment yield of 2.94 t ha^{-1} during the event. These data could not be correlated with precipitation, because storm lightening damaged the recording rain gauge.

4.3. Spatio-temporal variability of the most active geomorphic processes

The methods deployed in the *Barranca de los Pinos* catchment allowed a first quantification of the geomorphic activity in each of the three main zones characterizing the sandy slope gullies of this region (Fig. 3): steep gradient slopes, low gradient slopes and channels. This paper depicts preliminary results, which are shown as examples of the potential of this experimental catchment and of the methods deployed within it.

On the basis of the repeat oblique photographs obtained at fixed locations, it was observed that mass movements are active at: (ii) headwalls without caprock and (iv) sandy channel banks uncovered by colluvium.

As far as the scanning of high gradient slopes is concerned, two different high gradient units have been identified: i) headwall gully with caprock (Fig. 7a), ii) without caprock (Fig. 7b). These areas were scanned twice: in October 2009, from which a 'time zero' surface was obtained, and again in May 2010, with a modified land surface by mass movements. The data clouds from each of the scans produced a DEM surface. These DEMs were compared to determine topographic changes produced during autumn and winter. The scans did not include the entire deposits beneath the headwall, partly because of the interruption of the laser beam by pines crowns.

Hence, the comparison between presented scans refers only to the mid and upper headwall areas, excluding the depositional toe. These zones were scanned together and the distance from the scanning point was identical for both sites, so that their errors are also identical. As these selected zones had to be scanned from a relative large distance (on average 70 m), the involved errors are self-evidently higher than for other catchment areas scanned from nearby, due to the increase of the laser footprint area with distance. When comparing the 'before' and 'after' DEMs, two kinds of errors are involved: (a) the systematic error, calculated as the RMS of the height difference of targets measured with the total station and the TLS, and (b) the measurement error - the RMS of the position of the twin-held target located in the benchmarks in the two scans. The latter error is usually higher, as the twin-held target is to be perfectly vertical to match in the two scans. For both units, the systematic error was 7.2 mm, and the error registered between before and after the scanning was 10.7 mm. As total station heights were not measured in the nearly vertical escarpment but merely around it, the TLS-derived DEM error cannot be ascertained.

At various locations within the scanned areas, the differences between the two DEMs are larger than 10 cm, which is the spatial resolution of the first scan (Fig. 7). Hence, erosion larger than 10 cm occurred. The maximum retreat of 0.6 m occurred in the uncapped zone, while in the capped area the maximum retreat was 0.2 m. The sediment yield in the uncapped and capped areas was respectively 57.4 and 13.5 kg m^{-2} yr^{-1}. Erosion was produced at different locations: in the uncapped vertical walls and at the bottom of the inner permanent gullies of the capped slope (see Fig. 2c).

On low gradient slopes, micro plots installed on the HRUs showed the runoff and sediment yield responses to rainfall during a period lasting eight months, from October 2009 to May 2011. Admittedly, clearly defined relationships between runoff and rainfall or between sediment yield and runoff do not take place on these sands, which are typified by high infiltration rates. However, responses did vary according to the type of sand and its cover (Fig. 8). The ungullied slopes (HRU 1) produced more runoff, the exposed Segovia sands (HRU 2) is the unit yielding more sediment, and the sands covered by litter (HRU 6) produced the least runoff and sediment yield.

The upstream migration of the monitored knickpoint reflected channel dynamics. A 0.53 m yr^{-1} rate of upstream migration was obtained for the hydrological year 2009-2010 (Fig. 9). However this rate was temporally variable but it did not appear to vary systematically with rainfall. The upstream migration rate was higher than the average from the beginning of the hydrological year until the end of February 2010. From March 2010 until the end of May 2010 there was almost no movement, despite occurrence of precipitation events. The height of the knickpoint did not vary significantly during the entire monitored period.

Fluvial activity recorded at the outlet of the catchment is exemplified by the October 9th 2010, runoff event monitored in the right slot sampler (Fig. 10). This event was chosen because it was assessed as being representative of the median measured water depth. Indeed the selected runoff event had an average water depth of 24 mm, whereas the median of the water depth of all the monitored flow events since the sampler was installed (June 23rd 2009) until the end of 2010 was 26 mm. Furthermore, during this event the bedload samplers were not totally filled, so that it was possible to calculate total bedload. The 9.2 mm effective rainfall depth (calculated as the continuous rain shower since runoff started, considering that effective rain with less than 10 min without rainfall or without registering a 0.2 mm tip at the pluviograph) was preceded by 2.4 mm rainfall in the previous 24 hours. According to the 149 min duration and rainfall intensity (3.7 mm h^{-1}), the event has been calculated to have return period of one year [39]. The lag between the maximum rain intensity and peak discharge was 14 min. The catchment runoff coefficient for

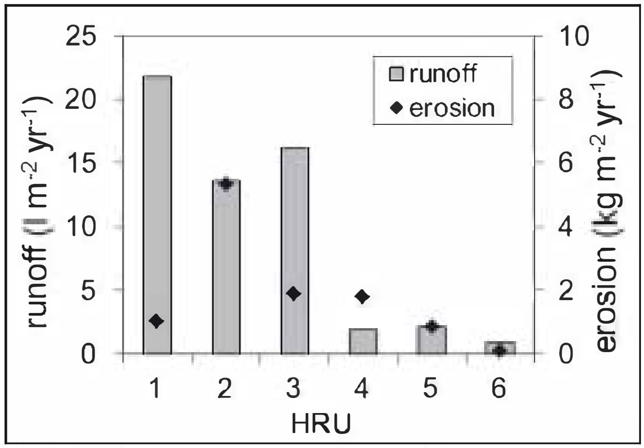

Fig. 8: Runoff and sediment yield produced in the six monitored Hydrological Response Units (HRUs): (1) ungullied slope covered by thick colluvium; (2) exposed Segovia sands; (3) thin limestone-dolostone colluvial deposits covering Segovia sands; (4) exposed Carabias sands; (5) thin limestone-dolostone colluvial deposits covering Carabias sands; (6) exposed sands under pine canopy covered by dead pine needles.

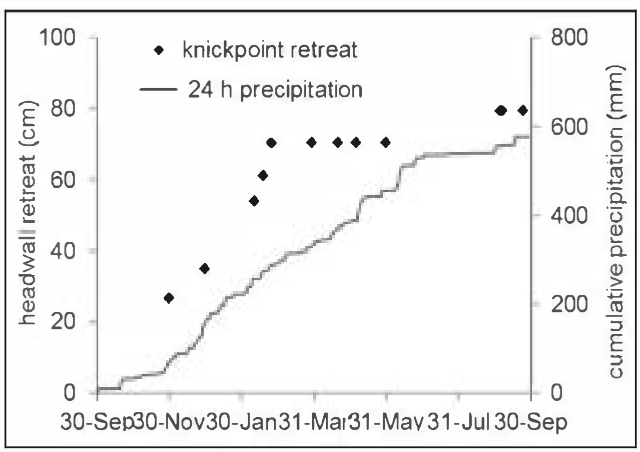

Fig. 9: Linear retreat of the nickpoint in the channel measured from April 2009 to September 2010

Table 3: HRUs runoff and sediment yields

ID HRU	mean runoff yield (mm yr⁻¹)	runoff/ rain (%)	runoff group	mean sediment yield (kg m⁻² y⁻¹)	sediment group	runoff-sediment 'interaction'	resistance group	sediment-resistance 'interaction'
1	21.8	3.28	I	1.0	b	fines decrease S.D.[1]	z y	none
2	13.6	2.04	I	5.3	a	positive	x y	none
3	16.1	2.43	I	1.9	b	fines decrease S.D.[1]	w	none
4	1.9	0.29	II	1.8	b	positive	x	none
5	2.1	0.32	II	0.9	b	positive	w	none
6	0.9	0.13	II	0.1	c	litter cover decreases S.D.[1]	z	positive

this event was 5.4 %. During this runoff event, the maximum 1-min bedload flux was 2.49 kg $s^{-1}m^{-1}$, and the mean bedload flux for the entire flow event was 1.02 kg $s^{-1}m^{-1}$. It is notable that bedload flux was generally sympathetic with water stage.

The bedload sampler was not entirely filled during this event (cumulative sampled bedload mass was 125 kg), hence the total event bedload sediment yield can be calculated based on the assumption that the sampler represents the entire cross section. The two siphoned water samples collected in this event had suspended sediment concentrations (SSC) of 31 and 27g l^{-1}. Solute concentration (S) of these water samples (0.23 and 0.18 g l^{-1}) were estimated based on the specific electrical conductance (EC) using the formula S (mg l^{-1}) = 0.65 EC(µS cm^{-2}). The total event sediment yield was 3.3 tons, of which 94.5 % was transported as bedload, 5.34% in suspension and 0.04 % as solutes.

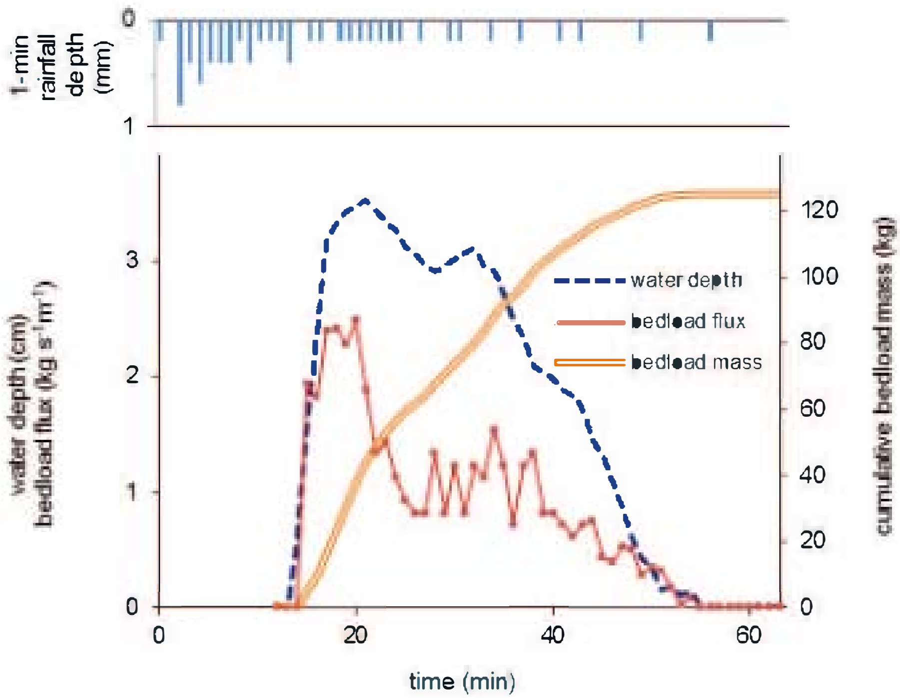

Fig. 10: Bedload flux and water discharge at the outlet of the *Barranca de los Pinos* Catchment during the 9 October 2010 flow event. The contemporaneous rainfall record is also shown

5. Analysis of the results: hydrological/erosional/ depositional responses

5.1 Identifying and describing the landforms and respective processes in the gullies

The catalogue of landforms that represent active geomorphic processes shows a very high diversity (Fig. 6) and a clear spatial pattern within the gullies, where three different parts, typical of any catchment with a torrential regime, are usually very well distinguished. Figure 11 shows a model of this organization.

5.2. Identifying and recognizing the most active processes

Although no volumetric quantification could be made of mass movements, repeat photography demonstrated how frequent rockfalls, mudflows and sandstone falls mobilized recognizable volumes of sediment to the bottom of the channels of the gullied network.

Sheet erosion data showed high variability, so the non-parametric Mann-Whitney test was carried out to compare the results. There were no significant differences among the divide, and the North and South facing slopes on each year, so that we interpret a greater importance of splash erosion compared to sheet erosion. The rationale behind this reasoning is that if sheet erosion were the main process, there should be higher erosion rates in the slopes, because to have sheet erosion in this setting, a minimum amount of watershed for runoff to form is needed, and this does not happen in these narrow divides. In other studies [40] is stated that high erosion rates in the divides imply an important role of the splash erosion, as narrow divides (of the magnitude of our study) are no prone to have sheet erosion.

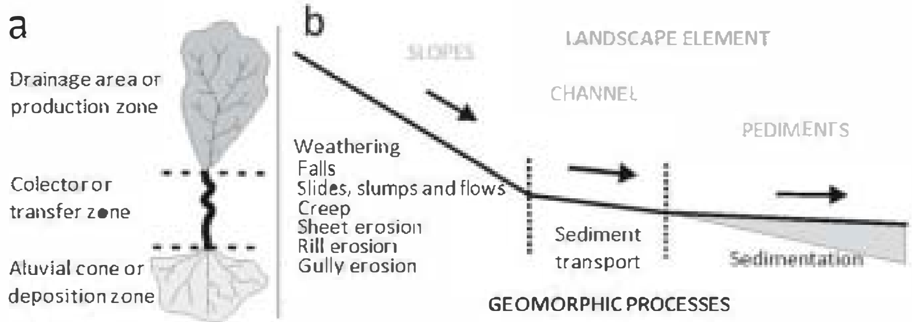

Fig. 11: Idealization of the studied sandy gullies, showing (a) their main three different zones and (b) their landscape elements and active geomorphic processes acting at each zone and landscape element

During the first hydrological year, there were statistical significant differences between the rates of erosion using pins and with pedestals, the median (6 mm yr^{-1}) lower in the pedestals. This difference may be methodological, as the pebbles on top of pedestals protected the soil under and nearby them until they were removed by erosion. From the measurements of pins, the erosion rates were significantly higher the first hydrological year: its median is 16 compared to 7 and 6 mm yr^{-1} for the two following hydrological years, respectively. These differences are unrelated to the annual rainfall, very similar for 2007/2008 and 2009/2010 and the rainier 2008/2009. The difference is explained by the occurrence of the extreme rainfall event of September 9, 2008.

Despite the fact that monitoring total sediment yield lasted merely three hydrological years, it included the record of the sediment yield of the extreme rainfall event mentioned above, which was more than half of the sediment recorded for the entire period. This stresses the need for long-term studies, because these extreme events yield most of the sediment. The GSD of the sediment stored in the totalizing samplers was mostly sand, although in the pit sampler also some silt and clays were collected as the water was also retained. In the gabion trap silts and clays were not collected, indicating that they were transported in suspension, whereas sands were transported as bedload.

In summary, the reconnaissance methods shed light on sediment movement within the system: sediments delivered from the slopes, mobilized by both gravitational and runoff processes, reach the gullied bottoms, from where they are evacuated mostly as bedload, conditioned by the fact that most of the gullied area is sand. Therefore, the use of these methods allowed formulating initial estimations of rates of activity of the most active processes acting within this set of gullies, as detailed hereafter.

5.3. Spatio-temporal variability of the most active geomorphic processes

No significant topographic changes were observed on the capped high gradient slopes between October 2009 and May 2010. Limited erosion occurred within small V shaped landforms in the capped high slopes (see Fig. 7a), indicating that erosion is mainly generated by water erosion and rill incision, not by gravitational processes. The erosion rate in the uncapped slope, steeper and with larger vertical areas than the capped slope, was four times larger than in the capped slope. The material eroded from the uncapped high slope produced an overhanging cliff and an additional vertical slope area, indicating that it was produced by gravitational processes such as falls favored by vertical fracture due to tectonics, litho-genesis, and decompression [35].

The non-parametric Mann-Whitney W-test was used to compare the median of sediment and runoff production rates between each pair of HRUs on the low gradient slopes. Results of the analysis (Table 3) show that there are two statistically significantly HRU groups in terms of runoff production. The higher one has a runoff rate higher than 10 mm yr^{-1} and it is composed by the ungullied slopes and the uncovered or colluvium-covered Segovia sands. The lower rates apply to the uncovered or colluvium-covered Carabias sands and the sands covered by dead pine needles.

As far as sediment yield is concerned, three statistically significant HRUs groups are recognized: (a) the Segovia sands with the highest sediment yield; (b) the sands covered by dead pine needles with the lowest sediment yield; and (c) the rest of the HRUs, with no statistically significant differences in sediment yields.

The non-parametric Mann-Whitney W-test was also used with respect to the surface mechanical resistance measured under wet conditions with a penetrometer. Three significantly different groups are recognized, herewith listed from lower to higher resistance: a) the two colluvium-covered sand units, b) the two exposed sand units, and c) sands covered by dead pine needles as well as the ungullied slope. Noteworthy is that the resistance of the ungullied slopes and the Segovia sands are not significantly different.

The rate of retreat of the gullied sand channel merely 0.53 m yr^{-1} (see Fig. 9), is slower than expected for non-cohesive sands. Moreover it is temporally discontinuous and unrelated to precipitation (Fig. 9) or water discharge. This fact may confirm the hypothesis that the rate of retreat is controlled by other factors that bond the sands, thereby delaying upstream knickpoint migration; these appear to be the horizontal, shallow roots which give strength and form the higher part of the knickpoint. Water flowing in the channels has been observed to infiltrate among the roots, eventually baring them (see Fig. 2d). The knickpoint maintains a vertical face, because scouring at the base occurs triggering subsequent falls. As already reflected, the process is temporally discontinuous and unrelated to precipitation or water discharge, so that no time pattern of occurrence could be established. The result is a horizontal upstream migration of the small waterfall. That no significant vertical changes occurred indicates that the kinetic energy at the knickpoint is dissipated, likely related to the high rate of bedload discharge and to the endless sediment availability.

The analysis of the October 9th 2010 bedload transporting flow event shows that initiation and cessation of the bedload transport is produced at different depths of flow. Bedload fluxes are very high (maximum recorded 2.49 kg $s^{-1}m^{-1}$). This is surprising considering the shallow (3 cm) water depth. Bedload was transported without interruption as soon as flow appeared. The bedload sedigraph displays a certain degree of pulsing, which may be related to the textural alternations identified in the bedload deposited in the samplers. No differences have been observed between the average grain size, being sand, collected in the automatic samplers and in the totalizer samplers.

Based on this single flow event with a return period of ca. one year, it is inferred that the proportion of bedload from the total sediment yield is very high for these shallow flows, corresponding to small return period events. This results from the mainly sandy lithology in the catchment, the high contribution of sandy sediment from the slopes to the tributary channels, and the quasi-infinite availability of sand in the main channel. For higher magnitude and lower frequency events, with expected higher water depths and shear stresses, it is expected that part of the sand will be transported in suspension, and the proportion of bedload compared to suspended, as the bed material is almost exclusively sand, will accordingly decrease.

6. Discussion

6.1. The deployed methods

Sheet erosion measured with pedestals has the advantage of no modification of the monitored surface, but 60 % of the 15 initially monitored pedestals were detached during the extreme event of September 9th 2008. Despite the known shortcomings of pins related to soil modification [41], they appear to be adequate in this area, where the clay content is low and erosion rates are high.

The two totalizer bedload samplers provided valuable information. However, the life span of the gabion sampler was short as it rapidly filled, so that the pit sampler is more adequate in this landscape. However its cleaning is both time and effort consuming [42]. This eventually led to the implementation of a device to measure bedload discharge automatically and continuously.

The measurement of the volume of sediments deposited in the alluvial cones was undertaken only once, as the road maintenance service cleaned it very fast. Indeed, this method has shortcomings also because it is possible to apply it only in selected (road) locations, although the information provided is useful for a qualitative evaluation of sediment yield in such large catchments.

Repeat photography from fixed points provided relevant qualitative information, as it has in other landscapes [43, 44]. The method is cheap and easy to develop, so that it is highly recommendable as a reconnaissance method.

TLS has proved to be adequate for obtaining high spatial resolution information about geomorphic evolution in non-accessible areas [45], such as gully headwalls, and without modifying the surveyed surface. Admittedly, obtaining high temporal resolution requires considerable time and effort, especially so in areas with difficult road and walking access, such as gullies and badlands.

The results obtained with the devices installed at the outlet of the catchment allowed characterizing continuous, bedload movement in a sandy channel. However, whereas bedload monitoring is continuous, suspended sediment was sampled only during hydrograph rise and at specific depths of flow, introducing vagary in the estimation of the suspended sediment-to-bedload ratio. Turbidity sensors coupled with pump samplers are required to obtain continuous records of suspended sediment concentration.

6.2. Geomorphologic rates in a sandy gullied landscape

Splash and sheet erosion rates are lower than the ones obtained with the same techniques in other sandy gullies [40]. In the sandy gullies of Central Spain divides and slopes are eroded at similar rates, whereas Crouch (1990) [40] shows higher erosion on divides than on the slopes. The average measured rate of sheet erosion (11.9 mm y^{-1}) is also higher than the only published erosion rates for the area (6.2–8.8 mm y^{-1}), determined by dendrogeomorphology analysis of exposed tree roots [46]. The difference may be due to the effects of the large event included in the monitored period. Because the rates obtained from dendrogeomorphology cover a larger time span (decadal), the effects of individual extreme events are 'blurred'.

Annual sediment yields calculated from totalizer sampler data are smaller than reported sediment yields for badlands of the same size (0.1 and 1 ha), *ca.* 12 % of the average rates in Mediterranean areas [47]. The monitoring period is admittedly very short although it does include one large event, so the difference is inferred to derive from the local sandy lithology, from which the majority of the sediment is transported as bedload rather than in suspension, the latter predominating in most gullies at the catchment scale (e.g. [48-50]). We interpret that this fact explain why we obtained lower rates – as most of the sediment eroded from the catchment is sand, which is transported as bedload, it has a lower transport efficiency compared with sediment transported in suspension, implying lower sediment yield at the mouth of the catchment.

High gradient slopes yield sediment by gravitational movements, as observed in other gullied areas, for instance, in French black marl badlands [51-53]. TLS-based accurate remapping of the topography representing nearly an entire year (inclusive of autumn, winter and spring, the more rainy and cold seasons when freeze and thaw occur) demonstrates almost no gravitational movement in the steeply inclined capped slopes, and minor erosion documented in the small channels incised into this steep slope (Figs. 7a and 7b). In comparison, high gradient uncapped slopes (65.5°) were more active than capped slopes (44.9°) as evidenced by gravitational movements (Fig. 7b). The capped high gradient slopes are more stable than the uncapped high gradient slopes, and the main operating geomorphological processes are markedly different between them even though they are (a) closely located, (b) of similar height (uncapped 11.6 m vs capped 13.3 m) and (c) of identical lithology. The capping is, thus, influential not merely on rates of erosion but also on dominant processes.

The results presented herein are based on accurate, but short term monitoring. Long term studies are needed to quantify slope evolution in capped and uncapped non-cohesive sands as the frequency of occurrence of rockfalls from the caprock is low [54]. Upon caprock failure, the magnitude of mobilised material may be large, thereby increasing the calculated erosion rates from such hillslopes. As rates of erosion in uncapped areas are higher in the short and medium term, uncapped gully headwalls are expected to retreat until the caprock is reached, thereby lowering rates of retreat. This cycle of slope retreat is supported by an assessment of the recent historic evolution of the gullied study area [12], reporting a 29 cm yr^{-1} maximum averaged rate of gully retreat, with reference to uncapped zones.

The retreat rates in the capped area are in the same range as the rates studied for similar slopes [55] and expressed as linear rates. The data on erosion from the uncapped zone are within the broad range of erosion rates of uncapped vertical gully cliffs [56] in Spain, although with different lithology (the latter eroding into cohesive loam, silt and clay) and climate (the latter more arid, Southern Spain). Accurate estimation of volumetric gully retreat by remote sensing requires a high spatial resolution of measurements [56]; hence, TLS-based monitoring provides higher accuracy than other techniques such as photogrammetry.

The two sand formations differ in their runoff response, higher runoff in Segovia sands relative to the Carabias sands. Interestingly, the thin colluvial deposits draping these two sandy formations do not substantially affect their runoff responses. The exposed Segovia sands produce the highest sediment yields, and belong to the group of higher runoff generation. The colluvium-covered Segovia sands and the ungullied slopes contain appreciable quantities of silts and clays (respectively about 12 and 30 % see Table 2) so that despite of higher runoff generation, production of sediment yield is intermediate. Both the colluvium-covered and the uncovered Carabias sands generate low runoff yields and intermediate sediment yield. This may be explained by the intermediate (4 and 12 % Table 2) content of silt and clays. The sands covered by dead pine needles produce low runoff and lowest sediment yields; the leaf coverage may be here the determining factor for this response, as shown elsewhere [57, 58].

The sediment yield from the low gradient slopes is on average 1.85 kg m^{-2} yr^{-1}, a very high sediment yield generated by a comparatively low mean runoff yield, 9.72 l m^{-2} yr^{-1}; in fact, 17 % of the total sediment yielded in all the plots was produced in events when no runoff was collected, so that they are interpreted to have been produced exclusively by splash erosion. This demonstrates the relative importance of this process, especially so in exposed sands; as stated elsewhere [59], sand is more easily detached by rain splash than other fine textured soils.

Among the low gradient slopes, the runoff coefficient is very low (0.13-0.32 % Table 1) for the uncovered and colluvially-covered Carabias sands as well as for the pine leaf-covered sands. The uncovered and colluvially-covered Segovia sands respond considerably more to rainfall, with runoff coefficients of approximately 2 %, rising to more than 3 % for the thick colluvium. These coefficients, as well as the catchment runoff coefficient for the analyzed flow event (5.4 %) are in the expected range (<7 %) for uncrusted sand [60].

The temporally discontinuous, unrelated to precipitation and overall low rate of knickpoint retreat in the gullied channel (Fig. 7), 0.53 m yr^{-1}, appears to be determined by roots protecting the soils from concentrated flow [61]. It is low compared to the expectation for a gully developed in non-cohesive sands; however, it is higher than the average (0.36 m yr^{-1}), monitored for short-medium terms in other loamy gullies of the Mediterranean area [56] and smaller than the average rate (0.63 m yr^{-1}) reported for Poland's loess gullies [62].

The event of the October 9th 2010 exemplifies bedload response, where catchment sediment yield is mainly comprised of sand bedload, with a maximum monitored flux of 2.49 ±0.04 kg s^{-1} m^{-1} and on average 1.02 ±0.04 kg s^{-1} m^{-1} (Fig. 10). These fluxes are particularly high when considering the shallow water depth (maximum 3.5 cm; average 2.1 cm), thus low shear stresses (average 13.2 kg $m^{-1}s^{-2}$, maximum 21.83 kg $m^{-1}s^{-2}$), compared to those often documented for initiation of motion of bedload in nature (e.g. [63-67]). Self-evidently this arises due to the differences on GSD, as those are gravel bed rivers or sandy gravel bed rivers, while the *Barranca de los Pinos* channel has a sandy bed, thus the hiding effect is irrelevant for initiation of motion and bed material size is smaller. Bedload transport is initiated almost immediately (1 min) after the flow arrives at a water depth of 1.6 cm; it lasts as long as the shallow water continues moving over the bed. The shear stress at the 1.6 cm water depth when initiation of movement is registered (0.85 kg $m^{-1}s^{-2}$) is higher than that expected for a critical shear stress estimated taking into account the dimensionless critical shear stress given by Shields, 0.6[68], or Meyer-Peter and Müller, 0.47 [69]. Bedload rates are also much higher than bedload transport rates measured in big sand bed channels as the Nile in Egypt or the Rhine in the Netherlands [70] where measured rates do not reach 0.1 kg $m^{-1}s^{-1}$, as the *Barranca de los Pinos* has a larger longitudinal slope.

The sediment yield for the sampled flow event presents an uncommonly high ratio of bedload relative to suspended sediment. The ratio for the sample event is an approximation not merely because it is a single event, but also due to the nature of suspended sediment measurements in this study. Our reported ratio is higher than the very high published bedload ratio (65 %) reported for a hyper-arid area ([71]). Indeed, rivers in areas with Mediterranean to continental climates often deliver only a small fraction of their load as bedload [67, 72].

7. Conclusions

A detailed survey of 75 sandy has allowed first ever to identify, classify and characterize a very high diversity of both landforms and active processes (Fig. 6). The first approach to the quantification of the most active processes by reconnaissance methods yielded a first approximation of rates for sheet erosion and sediment yield for these landscapes. For the latter, a high magnitude and low frequency event contributed a high proportion to the total sediment yield, accentuating the need for longer term studies. Ours is a first quantification of the processes acting on sandy gullied catchments, a landscape about which few studies have been undertaken, and it is the first study of such landscapes in a Mediterranean region [47]. Unlike the few prior studies on these rare landscapes, an attempt has been made to quantify the main operating geomorphological processes, among others by the use of some novel techniques, providing admittedly preliminary but rather accurate and detailed rates of runoff yield and sediment transport.

The hypotheses raised after analyzing the results of reconnaissance methods were confirmed: among the varied monitored landforms, high gradient slopes are the most active landform units, specifically the uncapped slopes. Differences in runoff and sediment yield among low gradient slopes point towards the importance of lithology and cover, evidently splash erosion is more important than runoff in sandy slopes and divides.

Most of the sediment yield is transported as sand bedload. Bedload discharge is generally high, higher than in other monitored permanent or ephemeral rivers for such low shear stresses, water depth and discharge. This is due to the nature of the bed material ¾ sand with hardly any gravel and a moderately high slope. An analysis of all the monitored events (all of them shallow) is required to determine which bedload formulae is most suitable for these channels and to obtain an evaluation of the proportion of bedload in increasing flow events. This may be useful for local reclamation projects in quarries, specifically for the design and dimensions of their settling pools.

The first results on geomorphological processes in the *Barranca de los Pinos* experimental catchment confirm the hypothesis of high geomorphic activity in this studied environment, a formidably beautiful landscape of sandy gullies, different and henceforth to be observed, monitored and overall researched for its singularities as well as similarities with other landforms.

Acknowledgements

This study has been funded by the Research Projects CGL-2006-07207 and CGL2010-21754-C02-01 of the Spanish Ministry of Science and Technology. The authors acknowledge the comments made by the editor, Hervé Piégay, and two anonymous reviewers, considerably helped to improve the original manuscript; also the kind collaboration of Cristina Martín-Moreno, Miguel Ángel Sanz-Santos, Carlos de Andrés, Fuencisla Vicente, Néstor Hernando, Ignacio Zapico, Sandra Martínez-Pascual, Jorge Martín and Javier Lucía for their help in the field work and Mathieu Labbe, Pauline Leduc and Laurent Hardy for the translation of part of the text into French.

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